Computational Fluid Dynamics for Brain Circulation and Aneurysm with Therapeutic Devices

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Summary

We analysed fluid dynamics at brain arteries having multiple inflow and out flow like Willis ring based on clinical imaging modalities. In addition, we analysed fluid dynamics with therapeutic devices like coils and stents to simulate their influences to blood flow.

3D CTA and MRA obtained three-dimensional structures of the brain vessels. The centreline was obtained from the three dimensional structure. Diameter of the blood vessels was measured by 3D CTA/MRA then smooth surfaced blood vessel models were created. For the fluid analysis, we developed a home brew software which can display parameters such as streamline, etc.

In addition, our CFD (computational fluid dynamics) software can work in collaboration with a CAD (computer aided design) software which we also developed (VCAD: Volume CAD). So, therapeutic devices such as coils, balloons and stents could be placed in the models and CFD analysis could be performed placing devices in the models.

The flow pattern in the complicated vascular structure could be calculated such as Willis ring which has multiple inputs like ICA, VA and multiple outlets like MCA and PCA with communicating arteries. CFD with therapeutic devices could also analysed with our system.

CFD including communicating arteries will assist the simulation of parent artery occlusion. CFD with therapeutic devices is helpful not only for simulation for embolization, but will help us to design therapeutic devices under computer simulation.

Introduction

GDC embolization is a safe and less invasive alternative for treatment of aneurysms [1].

Aneurysms are found at proximal part of brain vessels near circle of Willis. Willis ring has four input and a lot of outlets with communicating arteries. We have analysed flow pattern at the single inflow with multi-outlet modes which is not enough for whole of proximal brain arteries. In case of giant aneurysm, proximal occlusion is an effective treatment but our system could not simulate such situation. Here we planned to build a CFD system which can easily analyse complicated brain arteries. For finite element technique, three dimensional structures are built from medical imaging modalities such as three dimensional computer tomographic angiography (3D CTA) or three dimensional magnetic resonance angiography (3D MRA) [2].

However, the spacial resolution of such modalities are from 0.8 mm to 0.2 mm in general. So, a brain artery of 2 mm can have only

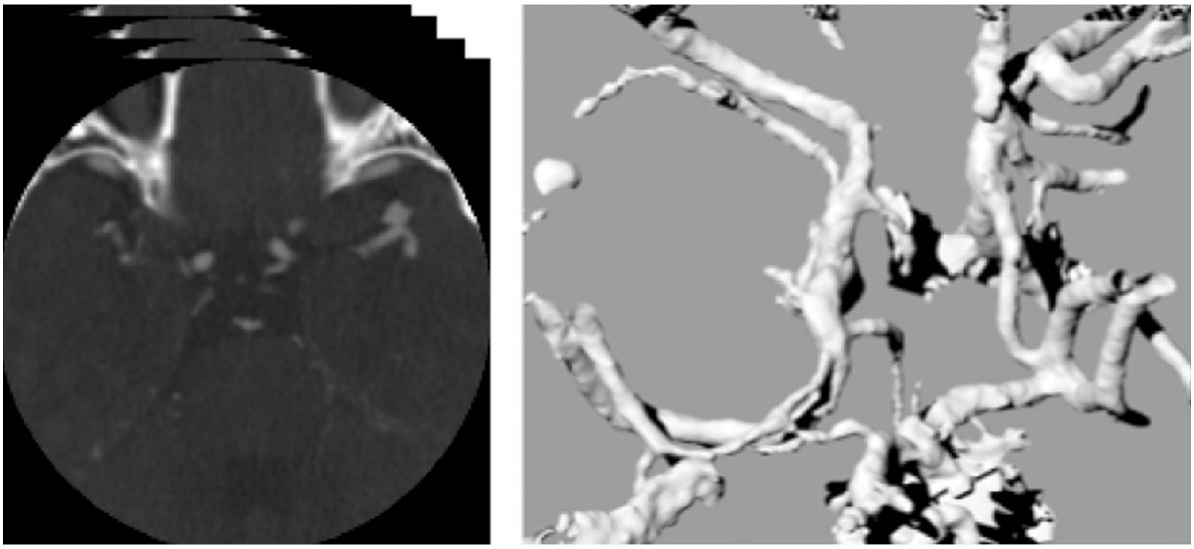

Figure 1 Left: Original slice data from 3D CTA. Right: Extracted vascular structure by Forge. The surface of vessels were not smooth.

three or ten voxels. It is not enough for computational analysis. We developed to build a model based on centre line of the vessels.

At the same time, therapeutic devices are rapidly developed. In order to assess the effect of such therapeutic devices. our CFD programme is designed to accept materials which are made by computer aided design (CAD) software. In Riken, we have already developing a CAD software, V-CAD (Volume CAD) [3] which is planned to work in corporation whit CFD software. Here, our system will support engineering of therapeutic devices.

Material and Methods

Basic three dimensional structure was obtained from 3D CTA or 3D MRA. The slice data complex is transferred to a workstation in DICOM format. The vascular structure was extracted by Forge (Studio PON, Rancho Santa Margarita, CA) (figure 1). Simulation models were built using Rhinoceos (Robert McNeel and Associates, North Seattle, WA), a 3D CG software. Centre skeleton line of vascular structure was drawn and smooth surfaced vascular structure was re-built from the skeleton line.

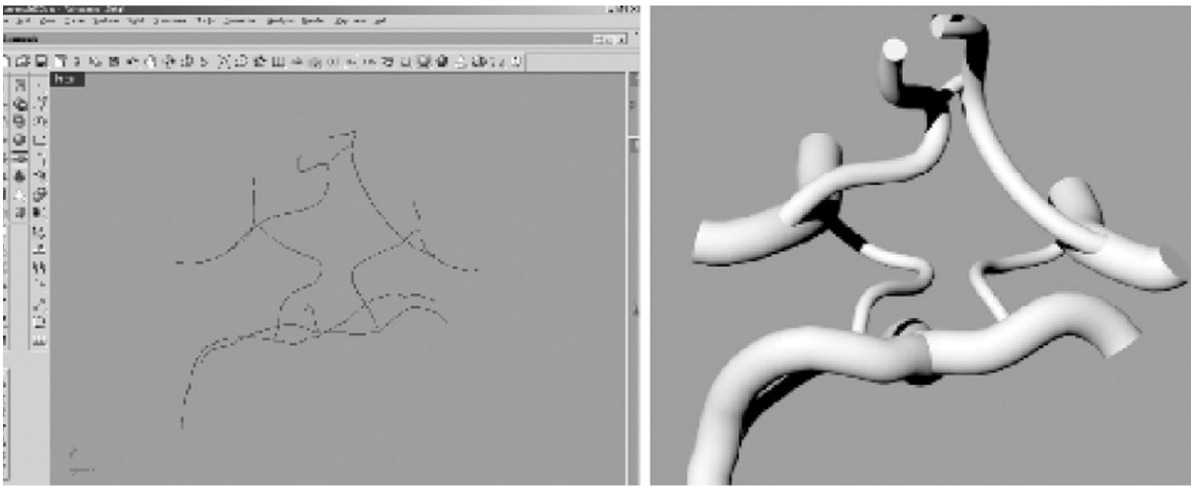

Figure 2 Left: Centre skeleton line of the circle of Willis based on the 3D extraction by Forge. Right: Smooth surfaced brain arteries for CFD.

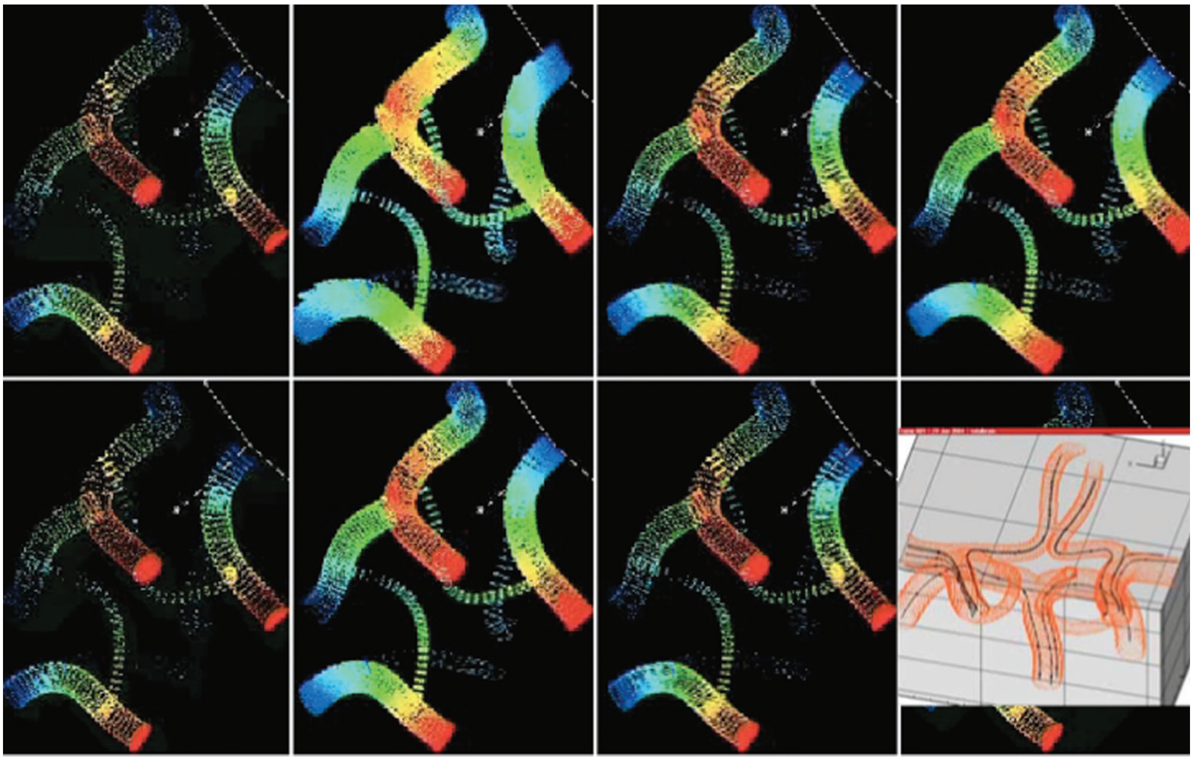

Figure 3 Pulsatile flow at the circle of Willis. Colour code indicated flow velocity.

Diameter of the vessels was given from 3D CTA/MRA. The 3D CG (Computer Graphics) of brain arteries were stored in IGES format (figure 2). Model of brain arteries in IGES format was read to V-CAD. V-CAD can generate mesh for CFD very easily.

The analyses of the fluid dynamics were performed by finite difference method. The governing equations are the 3D incompressible, unsteady Navier-Stokes equations. For the time integration terms, Euler implicit scheme is employed. The blood is assumed to be homogeneous, incompressible and Newtonian.

CFD itself was performed by our home brew software. Embolic coils, stents, microcatheters and non-detachable balloons were made by V-CAD and were possible to place in the vascular models.

Results

Flow pattern in the complicated vascular structure could be calculated such as Willis ring which has multiple inputs like ICA, VA and multiple outlets like MCA and PCA with communicating arteries. Pulsatile flow in the vascular structure was visualised (figure 3).

Therapeutic devices like coils, stents, microcatheters and balloon catheters were easily designed by CAD application. They are easily placed in the vascular/aneurysm models and CFd software can analyse their effect to the flow (figure 4).

Discussion

In our system, CFD including communicating arteries could achieved. It was not very easy for out previous system to calculate multiple outflow. Previous system handles direct three dimensional model It is possible to give high resolutional mesh for analysis while enough memory is available.

We could renew our system to have smooth surfaced model of brain arteries having multiple in- and out-flow. In this system, parent artery occlusion for large giant aneurysm could be simulated. However, for parent artery occlusion, collateral circulation through leptomeningeal anastomosis must be considered which

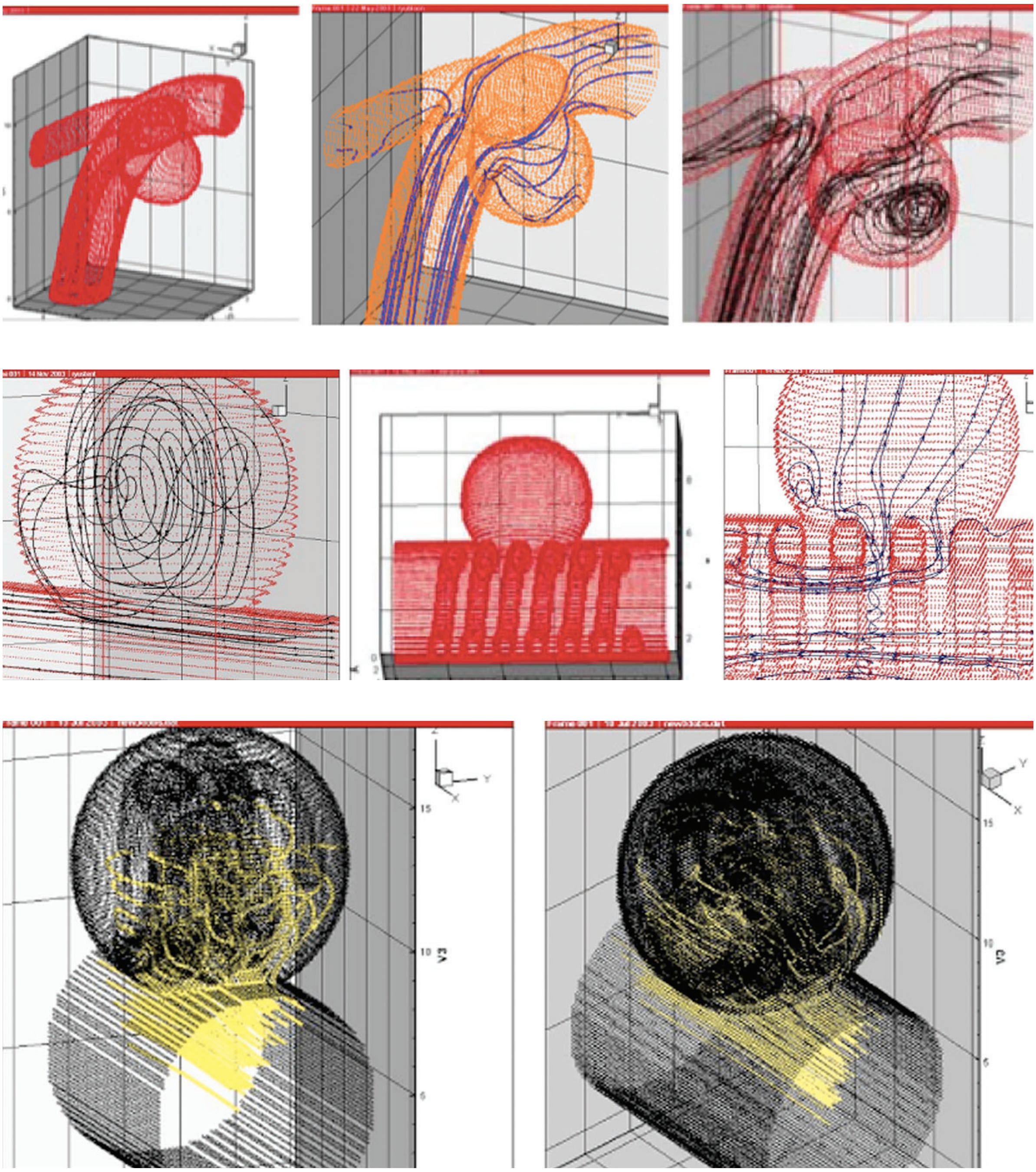

Figure 4 A) Aneurysm and non detachable ballon. Non detachable ballon affected the flow to produce different vortex in the aneurysm. B) Left: Flow pattern in the aneurysm (free flow). Centre: Coil stent made by V-CAD was placed at the neck of aneurysm. Right: Effect of the coil stent to the flow within the aneurysm.

will be another very tough work. One possible solution is to give virtual peripheral collateral vessels.

Our system has CAD system in itself. So it must be helpful to design therapeutic devices. We can design therapeutic devices by V-CAD and following the design, we can analyse their effect to flow while using our system. Combined with CAD application, mesh generation became very easy.

Moreover, giving virtual pathological vascular structure became also very easy. Using Rhinoceos and /or V-CAD, we can make virtual aneurysm, stenosis or other pathologies. Especially, affect to the flow after releasing stenosis was able to simulate easily.

This kind of numerical simulation has several problems. For example, blood is not Newtonian fluid, blood vessel must be elastic, therapeutic devices must be affected from flow, etc. We are planning to build CFD software having elastic vascular model.

Conclusions

We report our newly designed computational fluid dynamic software system from its input to final output. Our system can analyse complicated vascular structure like circle of Willis. Our system also able to analyse in combination with computer aided design application to be helpful for design of newly designed therapeutic devices.

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